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Evolution in the black hole mass–bulge mass relation: a theoretical perspective

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ABSTRACT

We explore the growth of super-massive black holes and host galaxy bulges in the galaxy population using the Millennium Run ΛCDM simulation coupled with a model of galaxy formation. We find that, if galaxy mergers are the primary drivers for both bulge and black hole growth, then in the simplest picture one should expect the $m_{\rm BH} - m_{\rm bulge}$ relation to evolve with redshift, with a larger black hole mass associated with a given bulge mass at earlier times relative to the present day. This result is independent of an evolving cold gas fraction in the galaxy population. The evolution arises from the disruption of galactic disks during mergers that make a larger fractional mass contribution to bulges at low redshift than at earlier epochs. There is no comparable growth mode for the black hole population. Thus, this effect produces evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation that is driven by bulge mass growth and not by black holes.

Key words: cosmology: theory, galaxies: evolution, galaxies: active, black hole physics

1 INTRODUCTION

Super-massive black hole masses are strongly correlated with their host bulge stellar mass, the so-called $m_{\rm BH} - m_{\rm bulge}$ relation (Magorrian et al. 1998; Marconi & Hunt 2003; Häring & Rix 2004). This is at least true in the local universe, but also expected to extend out to higher redshifts. This correlation suggests a common mechanism linking the growth of these two galactic components, with evidence proposing galaxy mergers as the most likely candidate. If true, and given that the global galaxy merger rate in a ΛCDM universe evolves strongly with time, one may ask if we should expect to see the $m_{\rm BH} - m_{\rm bulge}$ relation also evolve.

Support for the idea that bulges and black holes grow through mergers arises primarily from the success of numerical simulations and galaxy formation models in reproducing many observed galaxy scaling relations. Such works illustrate that much of the bulge mass of a galaxy can be accounted for by the disruption of disk stars from the merger progenitors, and merger triggered starbursts in the cold gas disk (Barnes 1992; Mihos & Hernquist 1994, 1996; Cox et al. 2004). As a growth mechanism for black holes, merger induced perturbations of the gas close to the central massive object can drive gas inward, fueling what is observed to be a 'quasar' period in a galaxy's history (see e.g. Kauffmann & Haehnelt 2000; Di Matteo et al. 2005).

In this simple picture the amount of cold gas present in a merging system plays a large part in how rapidly the black hole and bulge can grow. If the growth dependence for each is a simple constant scaling with gas mass, as is commonly assumed in many models of galaxy formation, then their mass ratio will, on average, be approximately independent of any evolution in the global cold gas fraction. This is because both bulges and black holes then co-evolve at a similar pace (drawing their new mass from the same gas reservoir). Furthermore, during a merger bulges will add to bulges, and black holes may coalesce. Thus, from this alone, one should expect little evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation.

In this paper we explore an additional growth channel through which bulges gain mass that black holes do not have. This is the disruption of merged satellite *disks*, and in the event of a major merger, the disruption of the central galaxy *disk*. The stellar mass in such disks will have previously never contributed to the $m_{\rm BH} - m_{\rm bulge}$ relation. If the bulge growth rate from such disrupted disks is not constant with time, then evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation can occur.

We investigate this behavior using the Millennium Run ΛCDM simulation (Springel et al. 2005) and a model for galaxy formation (Croton et al. 2006). This model follows the growth of galaxies (including their individual disk, bulge and black hole components) from high redshift to the present day, and provides a solid framework within which to undertake our analysis. The results we find, however, are not be unique to our particular implementation of the galaxy formation physics but arise from the simple assumptions described above regarding black hole and bulge growth in galaxies. Our aim in using this particular model is to illus-

trate what one may expect to see if these underlying growth mechanisms turn out to be true.

This paper is organized as follows. In Section 2 we briefly describe the Millennium Run ΛCDM dark matter simulation and our model of galaxy formation, including the simple implementation of bulge and black hole growth. In Section 3 we will use this model to investigate how black hole and bulges co-evolve together in the galaxy population from high redshift to the present. We finish in Section 4 with a discussion of the $m_{\rm BH} - m_{\rm bulge}$ relation in light of these results.

2 GALAXY FORMATION IN A COSMOLOGICAL CONTEXT

The galaxy formation model we use to study the $m_{\rm BH} - m_{\rm bulge}$ relation is identical to that described in Croton et al. (2006) (including parameter choices), with the exception of one non-essential detail, discussed below. This model of galaxy formation is implemented on top of the Millennium Run ΛCDM dark matter simulation (Springel et al. 2005). Below we briefly outline the relevant aspects of the simulation and model to our current work, and refer the interested reader to the above references for further information.

The Millennium Run follows the dynamical evolution of 10^{10} dark matter particles in a periodic box of side-length $500\,h^{-1}$Mpc with a mass resolution per particle of $8.6 \times 10^8\,h^{-1}{\rm M}_\odot$. We adopt cosmological parameter values consistent with a combined analysis of the 2dFGRS (Colless et al. 2001) and first year WMAP data (Spergel et al. 2003; Seljak et al. 2005): $\Omega_\Lambda = 0.75$, $\Omega_{\rm m} = \Omega_{\rm dm} + \Omega_{\rm b} = 0.25$, $\Omega_{\rm b} = 0.045$, $h = 0.73$, and $\sigma_8 = 0.9$. Friends-of-friends (FOF) halos are identified in the simulation using a linking length of 0.2 the mean particle separation, while substructure *within* each FOF halo is found with an improved and extended version of the SUBFIND algorithm of Springel et al. (2001). Having determined all halos and subhalos at all output snapshots we then build the hierarchical merging trees that describe in detail how structures grow as the universe evolves. These trees form the backbone onto which we couple our model of galaxy formation.

Inside each tree, virialised dark matter halos at each redshift are assumed to attract ambient gas from the surrounding medium, from which galaxies form and evolve. Our model effectively tracks a wide range of galaxy formation physics in each halo, including reionization of the intergalactic medium at high redshift, radiative cooling of hot gas and the formation of cooling flows, star formation in the cold disk and the resulting supernova feedback, black hole growth and active galactic nuclei (AGN) feedback through the 'quasar' and 'radio' epochs of AGN evolution, metal enrichment of the inter-galactic and intra-cluster medium, and galaxy morphology shaped through mergers and merger induced starbursts. As galaxy mergers and the resulting growth of bulges and black holes are central to the questions at hand, we will now describe these in more detail.

2.1 A simple picture of black hole and bulge growth

2.1.1 The "static" model

A satellite galaxy orbiting within a larger halo will feel dynamical friction (Binney & Tremaine 1987) and eventually spiral inward to merge with the central galaxy of the system. Mergers are believed to trigger galactic starbursts, where some (perhaps large) fraction of the cold disk gas is converted into stars on a timescale much shorter than that typically found in quiescent star forming disks. To model this event, when a merger occurs we assume the following mass of stars are formed in a burst from the combined cold gas mass of the progenitor galaxies, as found in the SPH simulations of Cox et al. (2004):

$$\Delta m_{\rm starburst} = 0.56\ m_{\rm R}^{0.7}\ m_{\rm cold}\ , \tag{1}$$

where $m_{\rm R} = m_{\rm sat}/m_{\rm central}$ is the merger mass ratio of the merging galaxies, and $m_{\rm cold}$ the total mass of cold gas present during the merger. These stars contribute to the spheroid of the final galaxy. For the results presented in this paper, the typical mass of stars in a bulge formed through starbursts is $\sim 10\%$, which, from Eq. 1, indicates an average gas fraction in the merging progenitors of $\gtrsim 30\%$. This is consistent with smoothed particle hydrodynamic simulations of merging galaxies which suggest that such a gas fraction is required to explain the local Fundamental Plane (e.g. Hernquist et al. 1993; Robertson et al. 2005).

Mergers also perturb the cold gas disk, and this can trigger the accretion of gas onto the central super-massive black hole. Croton et al. (2006) showed that, under reasonable assumptions, merger triggered 'quasar' mode events are sufficient to reproduce the local $m_{\rm BH} - m_{\rm bulge}$ relation as well as the observed local black hole mass density of the universe. To include such events, we apply an empirical relation similar to that described in Kauffmann & Haehnelt (2000) and assume that during a merger the gas accreted onto the black hole is proportional to the cold gas present, but in a way that is less efficient in lower mass halos:

$$\Delta m_{\rm BH} = 0.03\ m_{\rm R}\ \left[1 + (280\,{\rm km\,s^{-1}}/{\rm V_{vir}})^2\right]^{-1}\ {\rm m_{cold}}\ , \tag{2}$$

where $V_{\rm vir}$ is the virial velocity of the system, and $m_{\rm R}$ and $m_{\rm cold}$ are defined above. Here, the coefficient 0.03 normalizes the $m_{\rm BH} - m_{\rm bulge}$ relation to match that observed locally. It is important to note that in this picture the ratio $\Delta m_{\rm BH}/\Delta m_{\rm starburst}$, i.e. the relative growth rate of black holes and bulges due to converted cold gas, is expected to be essentially constant and independent of redshift, even if the gas fraction itself changes with redshift (note that the virial velocity of a system is only weakly dependent on time).

In addition to starbursts, bulges also grow from the stellar remnants of merged satellites. In our implementation any existing satellite disk is permanently disrupted during a merger and its stars, whose orbits will be heavily randomized from strong tidal forces, are added to the final galaxy bulge. Furthermore, we assume that if the baryonic mass ratio of the merging galaxies is large enough a major merger has occurred. Major mergers are sufficiently energetic that the disk of the central galaxy is also destroyed and its stars added to the bulge: we trigger such events when $m_{\rm R} > 0.3$.

To summarize, aside from the benign contribution during mergers of bulges to bulges and black holes to black holes, bulges in our model grow through both starbursts and disrupted disks, whereas black holes grow only by accretion. Importantly, black holes have no comparable growth mode from disrupted disks, and in Section 3 we will explicitly show the significance of this effect. Finally, given that we have made no implicit assumption regarding evolution in the growth of either bulges or black holes, we hereafter refer to this model as the *static* model.

2.1.2 The "dynamic" model

The above model is not unique in its ability to reproduce the local black hole and bulge populations. In the next section we will find it useful to consider a variation to this model, which we call the *dynamic* model, in order to explore the sensitivity of our results to the input physics. This change is applied to Eq. 2 and assumes that gas disks are more centrally concentrated at higher redshift (Mo et al. 1998) and are thus more efficient at feeding the black hole during a merger. We incorporate this idea in the simplest possible way through a transformation of the feeding efficiency coefficient: $0.03 \rightarrow 0.01\,(1+z)$ (note that the change in coefficient renormalizes our result to remain on the observed local $m_{\rm BH} - m_{\rm bulge}$ relation). We point out that now, by construction, we have introduced an evolution to the $m_{\rm BH} - m_{\rm bulge}$ relation, and this evolution is will be dependent on an evolving gas fraction. Using both static and dynamic implementations of black hole growth our interest is to measure the strength of the change in the $m_{\rm BH} - m_{\rm bulge}$ relation under the above physical assumptions to gain a sense for the range of possibilities that may seen observationally.

2.2 A disclaimer

To keep our model as simple as possible we do not consider other processes through which bulges or black holes can grow. This includes the tracking of disk instabilities which contribute to the bulge, as used by Croton et al. (2006) (this is our only variation from their model). Importantly, we do not claim that other growth modes are not important to the $m_{\rm BH} - m_{\rm bulge}$ relation. Instead, we assume that mergers, as described above, are the *primary* mechanism that determines the mass history of the bulge and black hole components of a galaxy. This allows us to explore the degree to which merger triggered disrupted stellar disks are able to drive evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation. We do not rule out the possibility that more complicated processes cancel out this effect.

3 RESULTS

In Fig. 1 we plot the $m_{\rm BH} - m_{\rm bulge}$ relation of our semi-analytic model galaxy population at four epochs, $z = 0, 1, 3, 6$. The filled circles in each panel represent the static model described in Section 2.1.1, while the open squares show galaxies where evolution in the black hole feeding efficiency has been assumed, the dynamic model described in Section 2.1.2. For reference, the solid line gives the best fit through the observations of Häring & Rix (2004) for a sample of 30 galaxies in the nearby universe with well measured bulge and super-massive black hole masses. The local population of both models have been normalized to that found by Häring & Rix and thus match it reasonably well. Contrasting this to the $z=6$ galaxy population we find clear evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation, where even for the static case a change in amplitude is observed. For both both static and dynamic models this indicates that the characteristic mass of a black hole residing in a bulge of given mass is larger at high redshift than at low, with the difference between models coming only from the degree of evolution found. To quantify this evolution we perform a simple χ^2 power-law fit with unity slope to each result at each epoch, which we illustrate in each panel with long and short dashed lines for the static and dynamic models, respectively. These fits are limited to galaxies with $m_{\rm bulge} > 10^9 M_\odot$. We emphasize that, for both dynamic *and* static models, the amplitude of the $m_{\rm BH} - m_{\rm bulge}$ relation *decreases* with time, finally settling on the observed relation by the present day. This justifies the high normalization chosen in Eq. 2. Interestingly, both models show no significant change in slope with redshift.

To understand the origin of the evolution found in Fig. 1 we separate the mass growth to model black holes and bulges into their respective components. This is measured at each redshift by first independently summing the total mass contributed from each growth channel (i.e. starbursts or disrupted disks for bulge growth, merger driven accretion for black hole growth) to all galaxies with bulges having $m_{\rm bulge} > 10^9 M_\odot$. We then consider the ratio of total bulge to black hole growth from these channels (which is also the mean relative growth rate) to quantify which dominates and when. We do this first for the simplest case, the static model, now shown in Fig. 2. In the top panel we plot the ratio of growth rates, $\dot{m}_{\rm BH}/\dot{m}_{\rm bulge}$, for bulge growth through either starbursts (dashed line, Eq. 1) or disrupted disks (solid line), both relative to the single black hole growth mode of gas accretion (Eq. 2). (Note that we do not concern ourselves with growth from black hole–black hole or bulge–bulge merging, since, by definition, this does not change the $m_{\rm BH} - m_{\rm bulge}$ relation.) We find that the relative growth of bulges and black holes from the existing cold gas supply present during the merger is approximately constant with time (dashed line). This is expected (see Section 2.1.1) and simply reflects the fact that, although individually their growth rates can be strongly affected by an evolving cold gas fraction, when taken as a ratio this evolution cancels. In contrast, the $m_{\rm BH} - m_{\rm bulge}$ growth ratio from disrupted disks is a strong function of redshift, as demonstrated by the solid line, with a change of almost an order-of-magnitude between $z = 9$ and the present day. This increase is driven by bulge growth that arises from both merged satellite disks and major merger disruption of central galaxy disks.

The bottom panel in Fig. 2 illustrates how this translates into an evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation itself. Here we show the previous χ^2 power-law fits from Fig. 1 as a function of redshift (solid line) and 1σ scatter around the mean (dashed lines). The clear decrease in the amplitude of the $m_{\rm BH} - m_{\rm bulge}$ relation by a factor of approximately 3 tracks closely the increase in the growth of bulges from disrupted disks. This demonstrates the simple idea we set out in Section 1, that if mergers are the primary mechanism

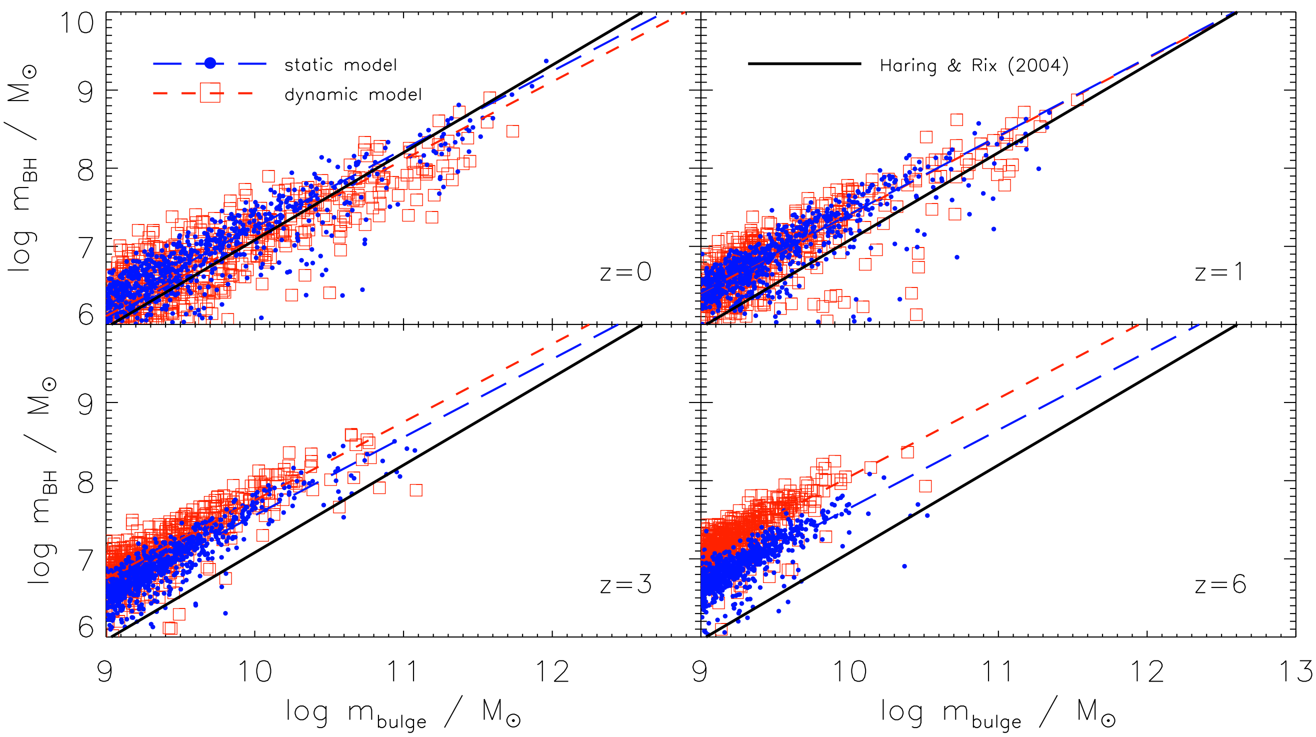

Figure 1. The $m_{\rm BH}-m_{\rm bulge}$ relation for model galaxies at four different epochs, $z=0,1,3,6$. Two realizations of the input physics are shown (see Section 2.1), a "static" model (circles) and an evolving "dynamic" model (squares). The best fit to the local universe observational result of Häring & Rix (2004) is given by the solid line, while the long and short dashed lines show a simple χ^2 power-law fit with unity slope to the static and dynamic model results, respectively. These fits have been restricted to galaxies with bulge masses $m_{\rm bulge}>10^9 M_\odot$. They highlight a clear evolution in the $m_{\rm BH}-m_{\rm bulge}$ relation in both models.

which shape both black hole and bulge growth in the galaxy population, then a larger fractional contribution to the bulge from disrupted disks should result in an inevitable evolution of the $m_{\rm BH}-m_{\rm bulge}$ relation. This holds true even when no explicit evolution the the growth modes of black holes and bulges is assumed.

In Fig. 3 we redo the analysis of Fig 2 now using the dynamical model described in Section 2.1.2. This allows us to explore the sensitivity of $m_{\rm BH}-m_{\rm bulge}$ evolution when some evolution in the black hole growth rate has been assumed. The top panel of Fig. 3 clearly shows a much stronger effect than that in the previous figure, with the relative growth of black holes and bulges from both the cold gas reservoir (dashed line) and disk disruption (solid line) changing with time with an additional factor of approximately $1+z$. This results in a significant boost to the previous evolution seen in the $m_{\rm BH}-m_{\rm bulge}$ relation, as shown in the bottom panel, with approximately an order-of-magnitude difference now predicted between high and low redshift. When one restricts the comparison to between redshift $z=1$ and the present day, the difference in amplitude is still a factor of ~ 2, which may statistically be an observable quantity in the near future.

4 DISCUSSION

The rapid increase of bulge growth at late times in our static model is a consequence of two well understood effects. The first is the steady rise in the star formation rate density of the universe from high redshift to approximately $z=1-2$. If one accepts, as a general rule, the conventional wisdom that the bulk of this star formation occurs in stellar disks, then the outcome is a strongly increasing growth of disk mass across the galaxy population with time. As disks grow the second effect then becomes increasingly important. This effect stems from the hierarchical nature of a CDM universe, where mergers become more frequent as the universe ages, assembling structure from the bottom up. As we discussed in Section 2.1, mergers also transform disks into bulges. Thus, at late times, a larger fraction of the total stellar mass in the universe becomes locked up in the spheroid component of the population relative to earlier epochs. This results in the accelerated bulge growth seen in Fig. 2, and which drives the evolution in the $m_{\rm BH}-m_{\rm bulge}$ relation shown in Fig. 1.

Observationally it is difficult to measure black hole and bulge masses. In the local universe Magorrian et al. (1998) estimate $m_{\rm BH}\sim 0.006\, m_{\rm bulge}$ from a sample 32 galaxies, while both Marconi & Hunt (2003) and Häring & Rix (2004) independently find $m_{\rm BH}\sim 0.002\, m_{\rm bulge}$ from improved measurements of ~ 30 galaxies. Although the statistics are still poor and the uncertainty large, locally at least all observations appear to be converging to a con-

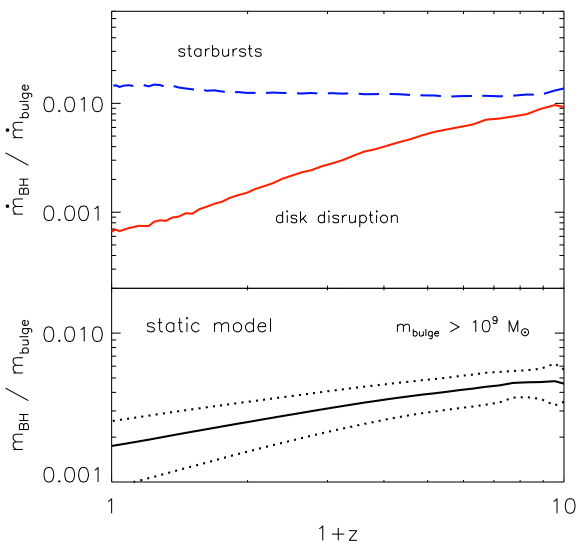

Figure 2. The static model described in Section 2.1.1. (top) The evolution of the relative growth rates for black holes and bulges, $\dot{m}_{\rm BH}/\dot{m}_{\rm bulge}$, for all galaxies hosting black holes with bulge masses $m_{\rm bulge} > 10^9 M_\odot$. As discussed in the text, black holes grow from merger triggered cold gas accretion. Bulges, on the other hand, grow from both merger induced starbursts and disrupted disks, so we plot these two growth channels independently (dashed and solid lines respectively). Disrupted disks are found to contribute a larger faction to the bulge at low redshift relative to high. (bottom) The accelerated contribution of disrupted disks drive an evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation, shown here using the χ^2 model fits from Fig. 1 across the entire redshift range. The dotted bounding lines show the 1σ scatter of galaxies along the relation.

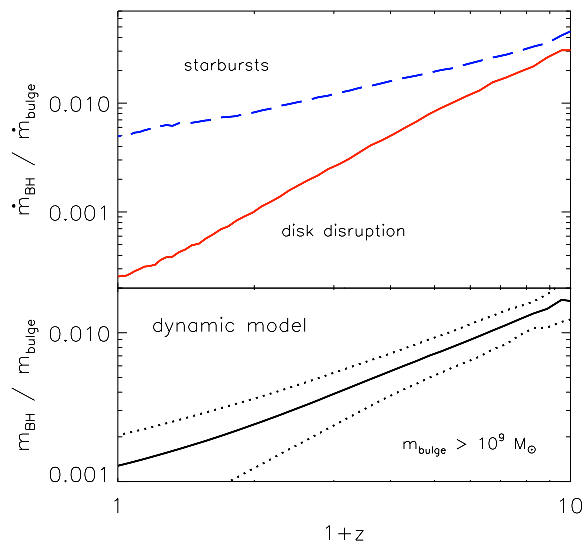

Figure 3. As for Fig. 2, however now showing the result for the dynamic model, where an evolution in the black hole feeding rate has been assumed (Section 2.1.2). Evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation is now much stronger than that seen previously.

sistent result. At higher redshifts the picture is much less clear. For example, Shields et al. (2003) claim little evolution in the relation can be inferred out to $z \sim 3$[1], and Adelberger & Steidel (2005) measure the quasar–galaxy cross-correlation function and find consistency with the local $m_{\rm BH} - m_{\rm bulge}$ ratio from a sample of 79 $z \sim 2.5$ quasars. On the other hand, Treu et al. (2004) see variations in the $m_{\rm BH}$–σ relation at $z = 0.37$, while McLure et al. (2005) measure some evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation using the 3CRR sample of radio galaxies. Similarly, Rix et al. (2001) use gravitational lensing to find that quasar host galaxies at $z \sim 2$ are much fainter than their low redshift counterparts containing quasars of similar luminosity, and Walter et al. (2004) find a significant deviation from the local $m_{\rm BH} - m_{\rm bulge}$ relation for a $z = 6.4$ quasar host galaxy. Future observations will need to clarify the exact nature of both the high redshift black hole and host galaxy populations.

Recent theoretical work to understand the cosmological assembly of stars and super-massive black holes have led to interesting results. Wyithe & Loeb (2003) present a model for super-massive black hole growth that successfully matches many local and high redshift AGN related observations. Their work results in a $m_{\rm BH}$–σ relation constant with redshift while predicting the $m_{\rm BH} - m_{\rm bulge}$ relation evolves as $m_{\rm BH}/m_{\rm bulge} \propto \xi(z)^{1/2}(1+z)^{3/2} \sim (1+z)^{1.15}$, where the final approximation is valid when $z < 2$, and $\xi(z)$ depends only on the cosmological parameters and is a weak function of redshift. An evolution of this kind would be consistent with the scaling assumed in our dynamical model (Section 2.1.2).

Similarly, Merloni et al. (2004) constrain phenomenologically the joint evolution of super massive black holes and their host spheroids by fitting simultaneously the total stellar mass and star formation rate densities as a function of redshift, as well as the hard X-ray selected quasar luminosity function. With the latter they assume that black holes grow exclusively through accretion. Assuming a present day disc to spheroid ratio of 0.5 (Tasca & White 2005), their work favors a model in which the $m_{\rm BH} - m_{\rm bulge}$ relation evolves as $\sim (1+z)^{1/2}$. This is a weaker effect than found by Wyithe & Loeb, however demonstrates both the range of evolution that may be expected, and most importantly, that such non-zero evolution can arise naturally from simple studies of black hole and bulge growth.

As discussed in Section 1, in a ΛCDM universe the effect described in this paper will be present in any model of black hole and bulge assembly driven by mergers. Indeed, this has already been seen in the semi-analytic model of Cattaneo et al. (2005) who find similar $m_{\rm BH} - m_{\rm bulge}$ evolution to that found here (compare their Fig. 6 with our Fig. 1). Unfortunately they do not discuss the origin of this behavior, but instead choose to focus on the disruption of galactic discs in relation to the scatter and slope of the relation. Cattaneo et al. grow bulges both as we do *and* from disk instabilities, which interestingly produces a bi-modal $m_{\rm BH} - m_{\rm bulge}$ distribution at high redshift. For simplicity we have removed bulge growth through disk instabilities (as originally used in Croton et al. 2006), although when included we also see such bi-modality. This bi-modal prediction of the high redshift $m_{\rm BH} - m_{\rm bulge}$ relation provides

[1] However see their most recent work (Shields et al. 2005)

a novel test of the mechanisms through which bulge growth may occur.

Theoretical arguments and numerical work have demonstrated that galaxy mergers are capable of simultaneously triggering growth in both bulges and black holes in a way so as to jointly reproduce many of their properties currently observed in the local universe. If mergers are the primary drivers of black hole and bulge growth in the galaxy population, then we have shown one should expect to see an evolution in the $m_{\rm BH} - m_{\rm bulge}$ relation which arises from an increasing contribution of disrupted disks to bulges as the universe ages. In this picture, *evolution in the growth of bulges drives an evolution in the* $m_{\rm BH} - m_{\rm bulge}$ *relation*, distinct from the growth rate of black holes. At the very least, even if the physics governing bulge and black hole growth turns out to be much more complex and cannot be expressed in a simplified manner (as is currently assumed by most models of galaxy formation), in a ΛCDM universe this effect should still be present and must be included in any interpretation of the $m_{\rm BH} - m_{\rm bulge}$ relation measured at different redshifts. We await future high redshift observations, e.g. the Galaxy Evolution from Morphological Studies (GEMS) project (Rix et al. 2004), to clarify the situation further.

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